A Study of Hypermixer and Aeroramp Fuel Injectors for Dual-Mode Scramjet

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論 文 内 容 要 旨

This thesis described research efforts on the development of a new aeroramp injector applied to a dual mode scramjet engine. The new aeroramp injector was proposed as replacing the cantilever ramp injector and the hypermixer injector, as such mixing enhancing injectors had a problem that the wedge shape of these injectors could not be maintained in a high enthalpy flow due to occurrence of hot spots.

In Chapter 1, the background and motivations of the present research, the past researches related to the present topics, and the problem and the objective of this work are shown.

In Chapter 2, experiments were performed to assess the performance of the proposed aeroramp injector in comparison to those of the hypermixer injector. Combustion experiments and mixing experiments in non-reactive flow were conducted. In the combustion experiments, wall pressure distributions and direct photographs of flame were obtained. In the mixing experiments, visualization of flow field by schlieren method was carried out. Also, gas sampling and aerodynamic probing were conducted to obtain mixing efficiencies, pressure loss parameters, and fuel profiles within the duct cross-section. From the results of experiments, the new aeroramp injector could not only avoid the loss of mixing performance resulting from collapse of the injector shape by forming a hot spot, but also could obtain better fuel/air mixing and combustion performances than the hypermixer injector in the wider total equivalence ratio without the additional total pressure losses.

In Chapter 3, the design parameters on the aeroramp injector proposed in the present study, were optimized in term of the combustor performances. Especially, the effects of the orifice design and ramp height on the combustor performance were focused on. Additionally, comparison between conventional injectors and the aeroramp injectors was done to assess the performance of the proposed aeroramp design. In this chapter, combustion experiments were carried out using injectors with seven different geometries. Wall pressure distributions in the combustor with each injector were obtained. The thrust coefficient increment was calculated, and by the one-dimensional analysis together, Isp was evaluated considering thrust generated by imaginary nozzle installed downstream of the combustor to access the effects of total pressure loss on the thrust production. In the comparison between the conventional injectors and the aeroramp injectors, the conventional perpendicular injector, the conventional swept-back injector, and the new aeroramp injector were used. Taking the contribution of the fuel jet momentum into account, the new aeroramp injector showed best performance. Evaluating the effects of the injection design on the nozzle thrust, the new aeroramp injector also showed best thrust production through the equivalence ratio range in the present study. Total pressure loss due to the installation of the ramp and associated shock wave generation was cancelled out by thrust production on the expansion ramp and higher combustion efficiency due to this injector configuration. In the optimization of the ramp height, the performance of injectors with three different ramp heights with the same orifice shape was compared. The results of the thrust increment by the combustor section showed that the small ramp could not have sizable effects on the thrust performance and large ramp resulted in a larger thrust increment during the combustion mode transition because pressure unbalance on the compression and expansion ramp surfaces acted favorable for thrust production. However, the installation of the large ramp had sizable effects on the thrust production of engines through the associated total pressure loss. During subsonic combustion mode, on the other hand, nozzle thrust with larger ramp was close to those in the cases with small and/or no ramps. With penetration of the shock train over the ramp, shock wave generation due to the airflow-ramp interaction was no longer sizable, and total pressure loss due to the ramp installation was mitigated. Between the injectors with small and no ramps, installation of the small ramp had little effects on total pressure loss and the consequent thrust production through expansion. In the optimization of the orifice alignments, firstly, the performances of a swept-back injector with the small ramp and the 4 holes aeroramp with the small ramp were compared. The swept-back injector with small ramp showed better thrust increment than the 4 holes aeroramp injector with the small ramp. A small number of holes was advantageous at low fuel/air dynamic pressure ratio because the fuel jet with large geometric shape will pass through the boundary layer and penetrate into the mainstream. The larger z direction velocity resulted in a generation of more intensive streamwise vortices in case with the swept-back injector with the small ramp. The variation of combustor net thrust in terms of Isp against fuel equivalence ratio were compared, and the swept-back injector with the small ramp showed slightly better performance than the 4 holes aeroramp injector with the small ramp, in whole equivalence ratio range. From the thrust performance in both the combustor and the imaginary nozzle, at low equivalence region, the 4 holes aeroramp injector with the small ramp showed higher Isp than the swept-back injector with small ramp. In the swept-back with small ramp, instead of improving fuel penetration at such a low fuel equivalence ratio, the fuel jet was directly exposed to supersonic flow of mainstream. Therefore, the total pressure loss increases more than the 4hole with small ramp. As a result, at low equivalence region, the 4hole with small ramp showed higher nozzle Isp than the swept-back with small ramp. Additionally, higher combustor Isp of the swept-back injector with small ramp led to larger total pressure loss by intensive combustion. Difference in the nozzle Isp between the 4 holes aeroramp injector with small ramp and the swept-back injector with small ramp became small with higher equivalence ratio. Next, the performances of the modified 3 holes aeroramp injector with the large ramp and the 4 holes aeroramp with the large ramp were compared. The 4 holes aeroramp injector with the large ramp showed slightly better combustor thrust increment than the modified 3 holes aeroramp injector with the large ramp at around $\phi = 0.2$. The modified 3 holes aeroramp injector with the large ramp showed lower nozzle Isp than the 4 holes aeroramp with large ramp injector throughout the fuel equivalence ratio in the present study.

In Chapter 4, focusing on the aligned compression - expansion short ramps characterizing the shape of the proposed aeroramp injector, moving of the separation point of the boundary layer in the combustor was visualized by schlieren method and time-variation of wall pressure depending on the movement of the separation point was obtained. From these results, the critical pressure-ratio of the boundary layer separation nearby those ramps was calculated. Values of the critical pressure-ratio obtained from experiments were compared with traditional three prediction equations (Mager's and Schumucker's, and Lawrence's equation) and applicability of these formulas was investigated. In the condition of 30 mm duct width, comparison between the experimental results and predictions showed that the Mager's equation and Schumucker's one could predict experimental values within the error bar range. Lawrence's equation under-estimated the value in almost all range of the local Mach numbers above the duct wall. Experimental data deviation between the prediction by Mager's equation and the experimental data was within 19%. Additionally, effects of the duct width and gas injection on the critical pressure-ratio were investigated. The duct width showed little effects on the critical pressure-ratio when reduced from 30 mm to 22 mm. Further reduction from 22 mm to 15 mm in the duct width caused little effects on the critical pressure-ratio on the compression ramp, but it resulted in an increased ratio on the expansion ramp. The gas injection from expansion ramp surface suppressed the boundary layer separation on the expansion ramp, as the injection induced streamwise vortices for intensive momentum exchange between the mainstream and the boundary layer flow. A higher injection pressure resulted in a higher critical pressure-ratio, as the streamwise vortices generation was enhanced with the higher injection pressure. In comparison to the combustion test results, the critical pressure for separation to move from the downstream to the expansion ramp, the critical pressure for separation to be anchored on the trailing edge of compression ramp, and the critical pressure for the shock train to penetrate the compression ramp, were predicted by Mager’s equation.

Chapter 5 is the conclusions. The major results obtained in this study are summarized.

論文審査結果の要旨

宇宙輸送機に空気吸込みエンジン技術を適用することで，機載酸化剤量を大幅に削減し，生じたシステム重量余裕を利用して輸送機の再使用化を図る研究開発が進められている。空気吸込みエンジンの中でもスクラムジェットエンジン，特に発熱制御よって亜音速燃焼も可能とするデュアルモードスクラムジェットエンジンは，輸送機の加速能力向上に有効である反面，エンジン内の滞在時間の短さゆえに燃焼促進，特に混合促進が必須の技術であることが知られてきた。本研究では，圧縮ランプ・膨張ランプの組み合わせにより縦渦を誘起して混合を促進する既存研究での Hypermixer 噴射方式において，その構成要素である楔面の焼損を避けるために，楔面圧縮ランプの一部を燃料ジェットにより空力的に形成する Aeroramp 方式を導入した新しい噴射方式（Aeroramp 噴射方式と称する）を提案し，実験によりその有用性を示している。本論文はこれらの研究成果をまとめたものであり，全編５章からなる。

第１章は緒論であり，本研究の背景，目的および構成を述べている。

第２章では，Hypermixer 方式と Aeroramp 方式を，燃焼実験と混合実験により比較している。燃焼実験においては火炎の直接観察と燃焼器内の静圧分布計測を行い，混合実験では断面内の燃料分布および静圧，ピトー圧分布計測と，シュリーレン法による可視化映像を取得している。両噴射方式に共通して，燃料流量の増加とともに，流れが膨張ランプに沿って流れる状態から，圧縮ランプ面後端で剥離して大規模剥離を形成する状態へと流れ場が変化することを示している。混合実験の結果から，前者の流れ場ではいわゆる逆回転縦渦対の形成が燃料と空気流の混合を支配する一方で，後者の流れ場では大規模剥離と空気流間の剪断混合が支配的であることを見出している。性能比較の結果から，本研究で提案した Aeroramp 噴射方式が，特に後者の流れ場において混合と推力発生に優れることを明らかにしている。これは，既存研究での提案に勝る混合促進が可能であることを示した重要な成果である。

第３章では，Aeroramp 噴射方式について，ランプ高さや燃料ジェットの配置などの設計因子を振った比較検討を，燃焼実験により行っている。まず円孔からの垂直および斜角噴射という基本的な噴射方法と比較して，Aeroramp 噴射方式が燃料ジェットの運動量まで含めると推力性能に勝ること，および全圧損失を考慮してなお膨張能力に勝ることを示し，ランプ部分の役割が大きいことを示している。次に Aeroramp 噴射方式においてランプ高さの影響を評価し，流れの境界層厚さを超えるランプ高さを設定することで，発生する衝撃波による混合促進などのより高い混合・燃焼器推力発生効果が得られる一方で，全圧損失の増加により膨張能力が劣ることを明らかにしている。更に，Aeroramp 噴射方式における燃料ジェットの噴射孔配置を変化させて性能変化を調べ，少ない孔数から噴射することで比較的高い推力性能を発揮できることを示している。これらは，当該噴射方式の設計の指針となる重要な知見である。

第４章では，前章までの知見から，ランプを囲む流れの状況が混合に大きな影響を及ぼすことに鑑みて，燃焼による圧力の上昇に伴う流れの変化の境界を予測する手法について論じている。空力的な実験によって圧力上昇とランプ周囲流れの剥離の発生の関係を調べ，既存研究で用いられた推算式により剥離の発生が予測可能であることを導いている。更に，流路の形状（断面の縦横比）や燃料ジェットの有無が剥離発生に及ぼす影響を調べている。更に前章までの結果に照らし合わせ，ランプ形状の設計により流れ場の状態を制御できる可能性を示している。これは，噴射方式の設計のみならず，噴射方式の利点を生かせる燃焼器の設計を可能とする有益な知見である。

第５章は結論である。

以上要するに本論文は，デュアルモードスクラムジェットの性能向上に資する噴射方式を提案し，他の方式と比較しての優位性を示し，更に設計の指針についてまとめたものであり，航空宇宙工学および宇宙推進工学に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。